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1 RANDOMIZED SUPERPIXELS TO ENHANCE MULTILEVEL IMAGE QUALITY  
2 IN ECONOMICAL, FAST INCREMENTAL-PRINTING ERROR DIFFUSION

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4  
5 RELATED PATENT DOCUMENTS

6  
7 Closely related documents are other, coowned U. S.  
8 utility-patent applications filed in the United States  
9 Patent and Trademark Office substantially contemporaneous-  
10 ly with this document — and also hereby incorporated by  
11 reference in their entirety into this document. One is in  
12 the names of Gil et al., and identified as Hewlett Packard  
13 Company docket number PD-60001011Z30, and entitled "DIS-  
14 CRETIONARY DOTTING FOR ARTIFACT CONTROL IN INCREMENTAL  
15 PRINTING" — and subsequently assigned utility-patent ap-  
16 plication serial 08/\_\_\_\_,\_\_\_\_, and issued as U. S. Patent  
17 6,\_\_\_\_,\_\_\_\_. Other such documents are in the names of  
18 Garcia-Reyero et al., and identified as Hewlett Packard  
19 Company docket number PD-60990037Z23, and entitled "IM-  
20 PROVEMENTS IN AUTOMATED AND SEMIAUTOMATED PRINTMASK GENER-  
21 ATION FOR INCREMENTAL PRINTING", and op cit. therein —  
22 and subsequently assigned utility-patent application seri-  
23 al 09/\_\_\_\_,\_\_\_\_, and issued as U. S. Patent 6,\_\_\_\_,\_\_\_\_.  
24 Another related document, filed somewhat later, is in the  
25 names of Gil et al., and identified as Hewlett Packard  
26 Company docket PD-60003198Z33, and entitled "\_\_\_\_\_

27 \_\_\_\_\_  
28 \_\_\_\_\_  
29 \_\_\_\_\_" — and subsequently assigned utility-patent  
30 application serial 09/\_\_\_\_,\_\_\_\_, and issued as U. S. Pat-  
31 ent 6,\_\_\_\_,\_\_\_\_.

32 Also related, coowned and wholly incorporated by ref-  
33 erence herein but filed earlier are U. S. utility-patent  
34 applications serial 08/960,766 of Bockman et al., relating

to use of lookup tables in error diffusion, and serial 09/384,735 of Askeland, proposing "very-high-ratio mixed resolution", and 09/184,577 also of Askeland, teaching random selection of colorimetrically equivalent superpixels; and also issued U. S. 4,\_\_\_\_,\_\_\_\_ of Lin introducing blue-noise characteristics in halftoning.

#### FIELD OF THE INVENTION

This invention relates generally to machines and procedures for incremental printing of text or graphics on printing media such as paper, transparency stock, or other glossy media, or textiles; and more particularly to a scanning thermal-inkjet machine (whether printer, copier or facsimile receiver) and method that construct text or images — but primarily high-quality photograph-like images — incrementally from individual ink spots created on a print medium, in a two-dimensional pixel array. The invention is especially valuable for very large images, and when processing speed is constrained by use of economical off-the-shelf processors without hardware assist, i. e. without the aid of an application-specific integrated circuit ("ASIC"), but it is not limited to use in connection with such constraints.

#### BACKGROUND OF THE INVENTION

(a) Orientation — The present-day marketplace for computer printing devices is extraordinarily competitive.



1 matrix-based binary printing, and performed the rendering  
2 and halftoning at a resolution lower than the final print-  
3 ing resolution — followed by some algorithm to artifi-  
4 cially increase the resolution when printing the image.

5 Combining dithering and single-level halftoning im-  
6 posed distinct limits to the image quality, and these are  
7 not acceptable in the present advanced generation of these  
8 devices. In addition, for lower-quality printmodes ren-  
9 dering was performed at lower resolution and then a method  
10 of pixel replication was used to print the lower-resolu-  
11 tion images at a higher printing resolution — a very fast  
12 technique.

13 Image-quality defects, however, included patterning  
14 in area fills due to dithering, and objectionable arti-  
15 facts arising from the replication. (Close inspection  
16 would reveal that 24 dot/mm pixels were identical across  
17 pixel groupings.) Naturally the method is inflexible in  
18 that the total number of drops printed in a certain area  
19 is the number of pixels set to one ("1") in the rendered  
20 image, times the scaling factor.

21 Also known are various other devices and systems in-  
22 volving use of smaller pixel structures. The first above-  
23 mentioned Askeland document, for example, substitutes sev-  
24 eral extremely asymmetrical small pixels for each square  
25 standard-size pixel to produce very fine actual (not simu-  
26 lated) horizontal resolution). Other artisans have pro-  
27 posed insertion of a very localized finer-resolution data  
28 grid (e. g. for antialiasing). As far as the present  
29 inventors are aware, no such prior technique was for the  
30 purpose — or had the effect — of expanding a rendering  
31 resolution into a simulated final printing resolution  
32 throughout an image.

33

1 (c) Conclusion — Former configurations produced  
2 strikingly attractive printouts at modest cost and thus  
3 were successful within the level of development of the  
4 market then prevalent, but cannot satisfy the more-strin-  
5 gent current market demands outlined above. Thus impor-  
6 tant aspects of the technology used in the field of the  
7 invention remain amenable to useful refinement.

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11 SUMMARY OF THE DISCLOSURE

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13 The present invention introduces such refinement. In  
14 its preferred embodiments, the present invention has sever-  
15 al aspects or facets that can be used independently, al-  
16 though they are preferably employed together to optimize  
17 their benefits.

18 In preferred embodiments of its first major independ-  
19 ent facet or aspect, the invention is a method for print-  
20 ing an image. The method includes the step of — for at  
21 least each colorimetric level that will be found in ren-  
22 dering the image — defining plural different superpixels.

23 As will be understood, the levels that will be found  
24 in rendering are part of a set that is ordinarily well  
25 known in advance of beginning the online steps. They are  
26 design elements of the overall operating method.

27 The invention also includes the step of generating or  
28 receiving data for the image. Another step is rendering

1 the image by a process that finds, for positions within  
2 the image:

3  
4 colorimetric levels, and

5  
6 a randomized value corresponding to substantially  
7 each found colorimetric level.

8  
9 The method also includes the step of applying the  
10 randomized value to select a superpixel from the plural  
11 superpixels for each found colorimetric level. Yet another  
12 step is printing the image using the selected superpixels.  
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14  
15 The foregoing may represent a description or definition  
16 of the first aspect or facet of the invention in its  
17 broadest or most general form. Even as couched in these  
18 broad terms, however, it can be seen that this facet of  
19 the invention importantly advances the art.

20 In particular, not only does it enable high-quality  
21 photograph-type printing by very fast error diffusion and  
22 with excellent color depth, using an off-the-shelf processor  
23 without hardware assist; but in addition this facet of  
24 the invention also provides a kind of simulated 24 dot/mm  
25 (600 dpi) rendition — out of a 12 dot/mm (300 dpi) rendition  
26 process. That is to say, a close inspection of the  
27 finished printing will show that in general adjacent 24  
28 dot/mm pixels are different from one another, even though  
29 the error diffusion is performed at 12 dots/mm. Thus this  
30 aspect of the invention does not suffer from the kinds of  
31 image artifacts associated with e. g. pixel replication.  
32

33 Although the first major aspect of the invention thus  
34 significantly advances the art, nevertheless to optimize

1 enjoyment of its benefits preferably the invention is  
2 practiced in conjunction with certain additional features  
3 or characteristics. In particular, there are two alterna-  
4 tive preferences as to the definition of superpixels:

- 5
- 6     ▪ in one preference, the superpixels defined for each  
7       available colorimetric level are all colorimetrically  
8       equivalent; and
- 9
- 10    ▪ in the other preference, the superpixels defined for  
11      at least one colorimetric level vary in colorimetric  
12      value — in such a way as to express that colorimet-  
13      ric level, on average, as a nonintegral number of  
14      colorant quanta.
- 15

16       Another basic preference is that the rendering step  
17      operate in a computational space that has one dimension  
18      for each colorant available, plus at least one dummy  
19      dimension which generates the randomized value. If this  
20      preference is observed, then there are two alternative  
21      subpreferences:

- 22
- 23    ▪ in one case, operation of the rendering step in the  
24      at least one dummy dimension includes using at least  
25      one least-significant bit that:
- 26

27               results from the rendering step in a colorant  
28               dimension, but

29

30               is substantially decorrelated from colorimetric  
31               levels found by the rendering step; and

- 32
- 33    ▪ in the other case, operation of the rendering step in  
34      the at least one dummy dimension includes deriving or

1 maintaining a matrix of randomized values; and the  
2 applying step includes mapping a particular location  
3 in the matrix to a particular position in the image  
4 — to choose a random value at the particular loca-  
5 tion in the matrix for selection of a superpixel to  
6 use at the particular position in the image.

7  
8 The second of these cases is also the second main aspect  
9 of the invention, stated below. Thus preferences as to  
10 matrix maintaining will be deferred for discussion with  
11 that second aspect.

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13  
14 In preferred embodiments of its second major inde-  
15 pendent facet too, the invention is a method for printing  
16 an image. Like the first, this method includes defining  
17 plural different superpixels for each available colorimet-  
18 ric level, and generating or receiving data for the image  
19 — and also printing the image using selected superpixels.

20 This method, however, also includes steps that are  
21 different. One of these is rendering the image by a  
22 process that finds colorimetric levels for positions with-  
23 in the image. Another is deriving or maintaining a matrix  
24 of randomized values.

25 Yet another step is mapping a particular location in  
26 the matrix to a particular position in the image. The re-  
27 sult of this step is choice of a randomized value, at the  
28 particular location in the matrix, for selection of a su-  
29 perpixel to use at the particular position in the image.

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31 The foregoing may represent a description or defini-  
32 tion of the second aspect or facet of the invention in its  
33 broadest or most general form. Even as couched in these



1 broad terms, however, it can be seen that this facet of  
2 the invention importantly advances the art.

3 In particular, this approach to obtaining randomized  
4 values for selection of superpixels is nearly free in  
5 terms of processing time, and quite economical in terms of  
6 information-storage requirements. The randomized matrix  
7 can be large if desired; however, it need not be very  
8 large.

9 The reason is that the results of the random selec-  
10 tion implied by this matrix are further scrambled by the  
11 later printmasking stage. Therefore any tiling of this  
12 matrix can be made to contribute little to eventual pat-  
13 terning in the image as printed.

14  
15 Although the second major aspect of the invention  
16 thus significantly advances the art, nevertheless to  
17 optimize enjoyment of its benefits preferably the inven-  
18 tion is practiced in conjunction with certain additional  
19 features or characteristics. In particular, preferably  
20 the matrix is derived or corrected to possess a blue-noise  
21 property of the randomized values.

22 Other basic preferences are that the mapping step in-  
23 clude interpreting:

- 24
- 25 ■ the value, found at each location in the matrix, as a  
26 pointer into a certain dimension of a table of super-  
27 pixels;
  - 28
  - 29 ■ an input or output colorimetric level, for the par-  
30 ticular position in the image, as a pointer into a  
31 certain dimension of the table of superpixels; or
  - 32
  - 33 ■ both — but with regard to different (i. e. first and  
34 second) "certain" dimensions, respectively.

1 Another preference is that the mapping step include inter-  
2 preting identification of a color plane being rendered, as  
3 a pointer into a third dimension of the table of super-  
4 pixels.

5 Yet another basic preference is that the mapping step  
6 include using the found randomized value for control of  
7 superpixels in all color planes. Still another is that  
8 the matrix include a set of smaller matrices, each of  
9 which contains randomized numbers corresponding to avail-  
10 able superpixels; and that successive ones of the smaller  
11 matrices be progressively stepped across the larger,  
12 first-mentioned matrix.

13 In this latter case, a number of subpreferences (not  
14 necessarily all mutually compatible) arise, namely that:

- 15
- 16     ▪ the stepped smaller matrices also be tiled across the  
17       larger matrix and wrapped around at an edge of the  
18       larger matrix;
- 19
- 20     ▪ the smaller matrices all be substantially identical;
- 21
- 22     ▪ the smaller matrices include plural different inter-  
23       leaved arrays (in which case it is also preferred  
24       that the plural different arrays be different sizes);  
25       and
- 26
- 27     ▪ the smaller matrices be one-dimensional matrices.
- 28

29 Another basic preference as to the second facet of  
30 the invention is that the superpixels defined for at least  
31 one colorimetric level vary in colorimetric value so as to  
32 express that colorimetric level, on average, as a noninte-  
33 gral number of colorant quanta. (As will be seen from  
34 earlier discussion, however, an alternative preference is

1 that the superpixels have substantially the same  
2 colorimetric value.)  
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5 In preferred embodiments of its third major independ-  
6 ent facet or aspect, the invention is a method for print-  
7 ing an image. Like the first two aspects, this method  
8 includes defining plural different superpixels for each  
9 available colorimetric level, and generating or receiving  
10 data for the image — and also printing the image using  
11 selected superpixels.

12 Additionally included is the step of rendering the  
13 image by a process that finds colorimetric levels for  
14 positions within the image.

15 The method further includes the step of selecting a  
16 superpixel from the plural superpixels for the found col-  
17 orimetric level. Yet further included in the method is  
18 the step of controlling the defining or selecting step, or  
19 both, to impart a blue-noise property to the selected su-  
20 perpixels — considered as an aggregate.

21 The method also includes the step of printing the im-  
22 age using the selected superpixels. The foregoing may  
23 represent a description or definition of the third aspect  
24 or facet of the invention in its broadest or most general  
25 form. Even as couched in these broad terms, however, it  
26 can be seen that this facet of the invention importantly  
27 advances the art.

28 In particular, this facet of the invention is  
29 particularly noteworthy in that it provides an extraordi-  
30 narily sophisticated solution to a subtle but important  
31 problem. This problem takes the visible form of distinct-  
32 ly different kinds of graininess, or clumping tendency, at  
33 different levels of colorant saturation.

1           In particular, randomness or so-called "noise" that  
2 is generated in ED when operating the invention near the  
3 error threshold values, is commonly white noise — i. e.,  
4 roughly flat in spectral distribution. (The reason is  
5 that the "error" being diffused is substantially zero, so  
6 that the color "signal" consists of values from a control-  
7 ling random number generator — and such values ordinarily  
8 are by definition random, i. e. white.) Noise from the  
9 error-diffusion process generally, however, is representa-  
10 tively blue noise.

11           Thus this third facet of the invention strongly fa-  
12 cilitates equalization of the graininess property for dif-  
13 ferent colorimetric levels, within each color plane. The  
14 result is to thereby make images appear more uniform in  
15 esthetic quality.

16  
17           Although the third major aspect of the invention thus  
18 significantly advances the art, nevertheless to optimize  
19 enjoyment of its benefits preferably the invention is  
20 practiced in conjunction with certain additional features  
21 or characteristics. In particular, preferably the defin-  
22 ing step includes screening the superpixels for spatial-  
23 frequency characteristics.

24           Thereby spatial frequencies, other than information  
25 in the image, appear substantially consistent in the  
26 printed image. The above phrase "other than information  
27 in the image" is discussed at the end of the detailed-  
28 description section of this document. (From the preceding  
29 discussion of the third main facet of the invention, it  
30 can be appreciated that a blue-noise characteristic in the  
31 process of selecting superpixels is desirable; however, it  
32 does not fully guarantee that the content of the superpix-  
33 els themselves will follow a blue-noise characteristic.)  
34 When this preference is observed, it is particularly

1 beneficial that the screening include spatial Fourier  
2 analysis.

3 Another preference, noted for the main aspects of the  
4 invention discussed above, is that the superpixels defined  
5 for at least one colorimetric level vary in colorimetric  
6 value so as to express that colorimetric level, on aver-  
7 age, as a nonintegral number of colorant quanta. In this  
8 way the superpixel approach to developing 24 dot/mm ap-  
9 pearance is in essence exploited to provide finer grada-  
10 tions in colorimetric level as invoked by input level  
11 variations throughout the image.

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14 In preferred embodiments of its fourth major indepen-  
15 dent facet or aspect, the present invention is apparatus  
16 for printing an image. This apparatus includes some means  
17 for defining plural different superpixels for each avail-  
18 able colorimetric level. For purposes of breadth and gen-  
19 erality in discussing the invention, these means will be  
20 called simply the "defining means".

21 The apparatus also comprises some means for generat-  
22 ing or receiving data for the image. Again for general-  
23 ity and breadth, these will be called the "data means".

24 In addition the apparatus includes some means for  
25 rendering the image by a process that finds colorimetric  
26 levels for positions within the image. These, again for  
27 like reasons, will be called the "rendering means".

28 Further included are some means for generating or  
29 receiving a randomized value for each of the positions  
30 within the image. These may be called the "random-value  
31 means".

32 The apparatus also includes "applying means" for  
33 applying the randomized value, in common for all color  
34 planes, to select for each color plane a respective super-

1 pixel from the plural superpixels for the found colorimetric level. Additionally included are "printing means" for printing the image using the selected superpixels.

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5 The foregoing may represent a description or definition of the fourth aspect or facet of the invention in its broadest or most general form. Even as couched in these broad terms, however, it can be seen that this facet of the invention importantly advances the art.

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10 In particular, application of a common randomized value for superpixel control in all control planes provides certain of the important benefits of plane-dependent error diffusion. The cost of actual plane-dependent operation, however, in terms of storage or processing capability/time, is far higher than the common-value technique of the present invention.

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18 Although the fourth major aspect of the invention thus significantly advances the art, nevertheless to optimize enjoyment of its benefits preferably the invention is practiced in conjunction with certain additional features or characteristics. In particular, preferably the applying means include means for employing a randomized value which corresponds to a compatible set of superpixels for different color planes.

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26 If this preference is followed, then further preferably the compatible set of superpixels includes coordinated placement of colorant quantity in the different color planes to achieve a certain image-quality objective. Still further if this subpreference is observed then preferably the coordinated placement includes elimination of substantially all drop-on-drop placement across planes, within highlight regions of the image.

1 Another basic preference, mentioned earlier with re-  
2 spect to the first three main facets of the invention, is  
3 that the superpixels defined for at least one colorimetric  
4 level vary in colorimetric value so as to express that  
5 colorimetric level, on average, as a nonintegral number of  
6 colorant quanta. The benefits of each main aspect can  
7 thus be enjoyed in combination with the enhanced smooth-  
8 ness of gradation achieved by generating superpixels whose  
9 average is a fractional colorimetric level; and this broad  
10 preference may be regarded as a fifth principal aspect of  
11 the invention.

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14 All of the foregoing operational principles and  
15 advantages of the present invention will be more fully  
16 appreciated upon consideration of the following detailed  
17 description, with reference to the appended drawings, of  
18 which:

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21  
22 BRIEF DESCRIPTION OF THE DRAWINGS

23  
24 Fig. 1 is a very general flow diagram comparing con-  
25 ventional binary halftoning with the multilevel, superpix-  
26 el halftoning of the present invention;

27 Fig. 2 is a diagram showing three mappings used to  
28 locate a superpixel table entry — and thereby a particu-  
29 lar superpixel — in matrix-based random selection of  
30 superpixels according to certain preferred embodiments of  
31 the invention, particularly employing a two-dimensional  
32 (2D) matrix;

1 Fig. 3 is a diagram of compatible superpixels for use  
2 in the several color planes of an image, for minimizing  
3 conflicts across planes in highlight regions of the image;

4 Fig. 4 is a reproduction of an automatically genera-  
5 ted two-dimensional (2D) FFT Fourier-analysis plot for  
6 level 1 of a two-by-two superpixel;

7 Fig. 5 is a like 2D FFT reproduction for level 2 of  
8 the Fig. 4 superpixel;

9 Fig. 6 is a like reproduction illustrating detection  
10 of asymmetry with the 2D FFT;

11 Fig. 7 is a graph of output from a modified radial  
12 spectrum (MRS) derived from the 2D FFT of Figs. 4 and 5;

13 Fig. 8 is a diagram of the square-annular integration  
14 geometry used in obtaining the Fig. 7 MRS;

15 Fig. 9 is a mapping diagram analogous to Fig. 2 but  
16 using a one-dimensional (1D) array or "vector" with wrap-  
17 around, instead of the 2D matrix of Fig. 2;

18 Fig. 10 is a graph of optical density vs. number of  
19 dots, for discussion of nonintegral-state linearization;

20 Fig. 11 is a diagram of superpixel random selection  
21 for expanding a single dot in a 12 dot/mm grid into a non-  
22 integral number, on-average, of dots in a 24 dot/mm grid;

23 Fig. 12 is a tabulation with accompanying diagram and  
24 arithmetic for generating a fractional number, on-average,  
25 of dot;

26 Fig. 13 is a perspective view of the exterior of a  
27 printing device embodying preferred embodiments of the  
28 invention;

29 Fig. 14 is a like view of a scanning carriage and me-  
30 dium-advance mechanism in the Fig. 13 device;

31 Fig. 15 is a highly schematic diagram of the working  
32 system of the Fig. 13 and 14 device, particularly as used  
33 to practice preferred embodiments of the third above-in-  
34 troduced aspect of the invention; and



Fig. 16 is a flow chart showing operation of the Fig. 13 and 14 device (but also including some off-line steps of preparation), particularly as used to practice the first, second and fourth aspects of the invention.

DETAILED DESCRIPTION  
OF THE PREFERRED EMBODIMENTS

1. MAPPING SPATIAL RESOLUTION TO COLORIMETRIC RESOLUTION

Actual spatial resolution needed for photograph-like reproduction is low (6 to 8 dot/mm, 150 to 200 dpi), provided that the number of possible color levels is high enough. The low resolution requirement applies particularly in large-format images as these are most commonly viewed at relatively greater distances — and also if the above-mentioned strict identity of adjacent pixels is avoided. Therefore actual imaging of details can be traded-off for more colors to enhance smooth colorimetric gradation.

This approach is pursued in the present invention. Preferred embodiments of the invention combine the benefits of multilevel error diffusion and fine colorimetric resolution, to virtually eliminate both patterning and color contouring.

The invention, however, is applicable to systems in which the final printing stage is actually either multilevel or binary. In other words, the multilevel ED processing may be only an intermediate step — and binary

operation may precede, or follow, or both. Needless to say, multilevel final output produces the finest quality.

The inventors' first effort to divert system capability from spatial resolution into colors was deterministic, mapping different intensity levels of the primary colors to a particular cell — denominated a "superpixel" — in the image. Unfortunately, interaction between regular patterns generated by the halftoning and various repeating physical errors in the printer (misdirected nozzles, printing-medium advance errors etc.) produced conspicuous artifacts.

## 2. RANDOMIZED MAPPING — BENEFITS AND DRAWBACKS

Those artifacts were significantly reduced through use of large randomized printmasks, according to the techniques described in the previously mentioned documents of Garcia-Reyero. The artifacts, however, still did not disappear completely.

By using plural different superpixels for each intensity level, and choosing among them at each pixel, the inventors obtained further reduction in regularity. At the same time, the differences among the superpixels also artificially provided a variation in level from pixel to pixel — thereby maintaining a seeming fine texture to the image even if very closely inspected.

An additional improvement was to make the superpixel choice randomly. (Random choice of superpixels to reduce banding is introduced in the previously mentioned Askeland document.) Thereby the system was made much more resistant to printer errors, and the fine texture made still more irregular and realistic.

1           Therefore the invention achieves, in an extremely  
2 economical system, an excellent rich environment for re-  
3 production of continuous-tone images. While presenting a  
4 simulated fine spatial resolution it is essentially free  
5 of patterning and contouring.

6           Randomizing the selection of superpixels, however,  
7 had two negative consequences. One was the computational  
8 overhead of generating a random number for each pixel.  
9 That overhead is large enough to eradicate the performance  
10 benefit over binary halftoning.

11           The second was much more subtle. When halftoning a  
12 patch, or a region in an image, with a constant color sim-  
13 ilar to one of the threshold levels defined in the error-  
14 diffusion process, the output was noisy.

15           In that case, no error is propagated and what appears  
16 is very noticeable white noise directly from the superpix-  
17 el selection. This in itself is perhaps acceptable, since  
18 noise occurs for colors intermediate between the threshold  
19 levels, too; however, the noise characteristics are dis-  
20 tinctly different.

21           While random clumping of dots at or near ED thresh-  
22 olds has a white-noise character, the texture for interme-  
23 diate colors has more high-frequency content — i. e. so-  
24 called "blue noise". Unexpectedly, this difference is  
25 readily seen and introduces an irrational-seeming fluctua-  
26 tion in overall appearance as colors change.

27           Various approaches to resolving these randomization  
28 problems are taken up in turn below. They include using a  
29 simple random-number generator, sharing the same random-  
30 ness for all color planes, and trying to add blue-noise  
31 character to the random-number generation process.

32           These efforts also made clear how important it is to  
33 choose a correct set of superpixels to represent a given  
34 level. This becomes increasingly more difficult with in-

creasing superpixel size — which in itself is desirable to reduce the effective resolution used in rendering — because the number of candidates for a given level grows very fast with superpixel size.

A starting point is four-weight binary error diffusion that somewhat randomizes the distribution of error by perturbing the ED weights. Serpentine raster processing was adopted to further reduce directionality artifacts. Extension of that algorithm to multilevel representations is straightforward; lookup tables are used in the error processing to avoid the computational burden of doing comparisons and distributing the errors arithmetically.

### 3. ALGORITHM OVERVIEW

Here are some terms that will be used in the explanation that follows:

- original resolution — resolution of the image before any scaling;
- rendering resolution — resolution of the image just before halftoning (this might include some scaling during the rasterization);
- device resolution — resolution of the image just before printing (this might be different from rendering resolution if some scaling is performed after halftoning); and
- superpixel — a mapping from the rendering to the device resolution, which expands into a two-dimensional cell each of the output levels of the halftoning.

1           Conventional binary halftoning 11-15 (Fig. 1) is  
2           distinctly different from a multilevel halftoning 21-27  
3           that uses superpixels. In the binary case, CMYK contone  
4           data 11 (eight bits per plane), assumed to be already  
5           color corrected, are scaled 12 to the device resolution.  
6           13. Then they are halftoned 14 using error diffusion to  
7           obtain one bit 15 per plane at the device resolution.

8           The present multilevel approach, by contrast, per-  
9           forms the scaling in two steps. The first uses a conven-  
10          tional method, bilinear scaling 22, to bring the image 21  
11          to the resolution 23 used for the halftoning (rendering  
12          resolution).

13          Next comes an ED variant 2, which generates five  
14          planes 25: CMYK, and "random", with m bits each — where  
15          m is small, i. e. 2, 3 or 4. (As to both conventional bi-  
16          nary technique 11-15 and the innovative multilevel method  
17          21-27, greater numbers of colorants are permitted. For  
18          instance six colorants CMYKcm including dilute cyan and  
19          magenta, are part of a particularly preferred embodiment.)

20          The random plane, together with a predefined set of  
21          superpixels, will later be used to scale up to the final  
22          device resolution by mapping each of the levels (defined  
23          by m bits) to a superpixel 26. The superpixel itself can  
24          be assumed binary, although this is by no means a require-  
25          ment of the invention. That is, in both the earlier bi-  
26          nary halftoning and the present multilevel halftoning, the  
27          final output can be four binary planes 27 with the same  
28          resolution (K·R).

29          For a presently preferred product embodiment, and  
30          also for the sake of simplicity in explanation, it can be  
31          assumed that the final device is binary. This means that  
32          for the rest of the system it is irrelevant that one in-  
33          termediate step uses multilevel processing — except that,

1 as noted earlier, this is a particularly economical, rapid  
2 and effective way to process the data.

3 If the final device supports multilevel printing,  
4 however, such printing is readily supported by providing  
5 multilevel (nonbinary) superpixels. Thus the invention is  
6 extremely versatile with regard to the final output form.

7 Multilevel ED with random superpixels has at least  
8 three major advantages:

9

10 (a) Reduce processing overhead — Scaling and half-  
11 toning with error diffusion constitute most of the compu-  
12 tations, in a color pipeline according to preferred em-  
13 bodiments of the invention. By using a lower resolution  
14 in both operations, it is possible to significantly speed  
15 up the processing.

16 In particular it was found that use of a 12 dot/mm  
17 four-level ED with superpixel output provided a 2½-fold  
18 throughput improvement over traditional 24 dot/mm binary  
19 ED (both using binary scaling to map a 60 Mbyte photo to  
20 an E-size sheet). Final image quality was very comparable  
21 for the two methods.

22

23 (b) Reduce bandwidth and memory requirements — Ex-  
24 pansion of the superpixels can be delayed until the last  
25 moment before printing, even on the fly with some hardware  
26 support. Even with no extra-hardware support the overhead  
27 of this expansion is small, given a fast processor.

28 The benefit of such delay is that the size of a swath  
29 before superpixel expansion is much smaller than after ex-  
30 pansion: 12 dot/mm with four levels (two data bits per  
31 pixel) is half the size of 24 dot/mm binary. The delay  
32 therefore reduces the memory needed, the disc bandwidth  
33 requirement for directing printing from it, or network

1 bandwidth for printing RTL (raster transfer language)  
2 plots, if they are in this format.

3  
4 (c) Minimize halftoning artifacts — The combination  
5 of serpentine raster processing, built-in weight randomi-  
6 zation and random superpixels significantly reduces most  
7 of the worm-like artifacts that standard ED techniques  
8 produce in highlight areas. Also, random selection of a  
9 set of compatible superpixels across color planes for each  
10 pixel is preferable to independent selection of superpix-  
11 els independently for each color plane.

12 Selection of compatible sets reduces problems of  
13 interactions of different planes. In particular, this  
14 strategy can be exploited to reduce graininess by avoiding  
15 placement of drops in one plane on top of drops in another  
16 plane in light tone regions.

17  
18 On the other hand, accompanying these three advanta-  
19 ges there is a disadvantage. Because rasterization takes  
20 place at lower resolution, notwithstanding the presence of  
21 a simulated high resolution, text and line art may not ap-  
22 pear as "crisp" as they would if full resolution were  
23 used.

#### 24 25 26 4. RANDOMIZATION TECHNIQUES

27  
28 Successful practice of preferred embodiments of the  
29 invention calls for generation of pseudorandom numbers  
30 quickly. It is also desirable that the numbers have cer-  
31 tain properties — such as limited low frequencies, which  
32 are more visible to the eye; and absence of any particular  
33 directionality, which could produce artifacts.

1           The overhead of random number generation is signifi-  
2 cantly reduced by using the same number for all the color  
3 planes (CMYK). This is equivalent to adding a fifth plane  
4 (R, for "random") that determines the superpixel selection  
5 for the other four, at each level.

6           As suggested earlier, this tactic has an interesting  
7 and very beneficial side-effect: it enables definition of  
8 a family of superpixels, one for each plane — that are  
9 likely to be printed together. The superpixels in each  
10 set can be designed to minimize interactions between color  
11 planes, so that some plane-dependent benefits are obtained  
12 even though the halftoning is nominally plane independent.

13  
14           (a) Standard random number generator (RNG) — The in-  
15 ventors experimented with several techniques for random  
16 number generation. One was to use an off-the-shelf libra-  
17 ry call, "lrand48", which provides a uniformly distributed  
18 sequence of pseudorandom numbers.

19           This module uses a linear congruential algorithm with  
20 forty-eight-bit integer arithmetic. It gives excellent  
21 quality, with no visible artifacts due to correlation  
22 across lines — with an important exception, mentioned  
23 earlier:

24           When halftoning patches with colors near a halftoning  
25 threshold, the error itself is zero. What is seen, then,  
26 is a pattern determined exclusively by the spectral prop-  
27 erties of the random-number sequence.

28           In the present case that sequence is essentially  
29 white noise, which includes a relatively large low-fre-  
30 quency content, not very pleasant to the eye. This appea-  
31 rance is different from the basic texture of error diffu-  
32 sion, which is a blue-noise characteristic.

33           The white-noise characteristic is particularly annoy-  
34 ing in smooth gradients crossing a halftoning threshold.



1 The reason is that in traversal of the threshold level,  
2 the noise texture of the printed image changes from blue  
3 to white and then back again to blue.

4 The transition is thereby made very visible. It  
5 would be possible to apply a high-pass filter to the ran-  
6 dom-number sequence, but after preliminary effort this so-  
7 lution appeared too expensive.

8 Another problem was that the off-the-shelf RNG was  
9 too slow, losing all the benefits of lower-resolution ren-  
10 dering. A related alternative was to reduce this overhead  
11 by precomputing a random sequence and reusing it across  
12 lines, but then correlated artifacts began to appear. The  
13 off-the-shelf RNG was then abandoned, and work started on  
14 a custom RNG.

15  
16 (b) Error-diffusion RNG — Preferred embodiments of  
17 the invention need only a few random bits (typically two)  
18 to guide the superpixel selection. It is well known that  
19 the least significant bit (LSB) of typical images carries  
20 very limited image content, and this is even more clear  
21 after applying complex scaling (*i. e.* bilinear).

22 This fact implies that the LSB of each error value  
23 propagated during the ED halftoning of images is nearly  
24 uncorrelated with the original image and thus provides a  
25 reasonable degree of randomness. In other words, the  
26 proposition is to use part of the ED error itself as the  
27 random bits.

28 The favorable properties of the LSB can be enhanced  
29 by performing an exclusive-or (XOR) function on the error  
30 LSBs across the four color planes, and initializing the  
31 error buffer with small random values instead of zeroes.  
32 In practice the cost of doing the XOR and masking the LSB  
33 was negligible — no extra memory-access call was needed,

1 and the quality of the output for images was very nearly  
2 as good as with the off-the-shelf RNG.

3 Unfortunately, when applied to solid patches the re-  
4 sults were not as good as for images. In particular, when  
5 the solid-patch color was exactly the same as one of the  
6 halftoning threshold levels — so that no error was to be  
7 propagated — some correlated artifacts could appear.

8 This problem could be easily fixed by monitoring when  
9 the error was consistently zero, and in that case fall  
10 back to the off-the-shelf RNG. The extra comparisons  
11 would carry some penalty, and some peculiar cases would  
12 operate slowly; but overall this technique would be faster  
13 than the first method.

14 Another problem with the ED RNG was the same as dis-  
15 cussed above for the standard RNG, relating to white-noise  
16 character of the output when operating near an ED thresh-  
17 old. The cost of dealing with the noise characteristic  
18 here too was deemed excessive.

19  
20 (c) Matrix-based RNG — One way to impart a blue-  
21 noise property to a sequence of random numbers is to pre-  
22 compute a matrix of values with that property. One way to  
23 begin is with a blue-noise dithering matrix (introduced by  
24 the previously mentioned document of Lin).

25 Levels in that matrix can be collapsed until what  
26 remains are all entries ranging from unity through the  
27 number of superpixels, and roughly the same number of en-  
28 tries per level. That collapsed matrix 162 (Fig. 2) can  
29 be used to generate pseudorandom superpixels 166D'.

30 Given a pixel 171 with coordinates  $x$  and  $y$  we index  
31 (172r for rows and 172c for columns) inside that matrix  
32 with the coordinates relative to the matrix, obtaining a  
33 random entry 173. The superpixel 166D' that will be  
34 inserted in position for a particular color plane 91-94

(Fig. 3) is obtained by entering a superpixel selection table 163 with:

- that random entry 173 as an abscissa pointer 174,
- the intensity level 171 as an ordinate pointer 179, and
- if desired, the plane being rendered as plane pointer (not shown).

The last-mentioned choice is actually not necessary in preferred embodiments, since the same random entry advantageously is used for all planes to gain the plane-dependent properties noted earlier.

This process is somewhat similar to now-conventional dithering with a blue-noise matrix — with the important difference that no threshold operation is required at this point. In addition, the size of the superpixel tables 163 is kept small because the range of intensity levels 171, 179 has already been heavily reduced by error diffusion.

Therefore this operation can be performed very quickly and without significant memory overhead. Furthermore this methodology avoids the previously mentioned difficulties of mismatched noise characteristics.

Using this method in ED of a solid patch that is exactly the color of an ED threshold, however, does produce a repeated pattern. In practice such a repetitive pattern can be hidden by using a large enough random matrix 162 — and a matrix of two hundred fifty-six values has been found a reasonable size for this purpose.

(d) Randomization by 1D arrays — An alternative is a scheme using a one-dimensional array or so-called "vector"

41 (Fig. 9), or several such arrays of different lengths, with wrap-around. In a single-array case, the array 41 has length  $V_x$  and is filled with random numbers from one through the maximum number of equivalent superpixels.

Typically random numbers chosen for the array have a high-frequency spectral characteristic, in order to reduce graininess. The index into this array is obtained by tiling (Fig. 9) the page 162' with the array, but wrapping the array sequence around 42 at the end of the line (page width is  $W_x$ ). In the illustration what is tiled is the array sequence rather than any individual array, since an integral number of arrays is spaced to fit into the page width as shown.

In practice, the index into the array is computed from the input pixel coordinates  $(x,y)$  by counting the number of pixels from the top left corner of the page to this pixel (while traversing the page left-to-right and top-to-bottom), and calculating the relative offset of this value inside the array (i. e.,  $(y \cdot W_x + x) \bmod V_x$ ). The random number 173, 174 in the array 162' corresponding to that index, together with the input level 179, is used to select the superpixel cell 91, 167A from a lookup table 163. Typically  $V_x$  and  $W_x$  are chosen relatively prime of each other so that the pattern does not repeat across many lines.

This scheme can be generalized by using multiple 1D arrays (i. e.,  $N$  arrays), possibly of different sizes, and using array  $i$  for rows of the input image  $i$ ,  $i+N$ ,  $i+2N$ , . . . wrapping this array around within this subset of rows. (Other, less-systematic stepping is also feasible and may be preferable.) This interleaving makes the pattern even less repeatable across lines.

1 5. SUPERPIXEL SELECTION

2  
3 Although the random matrix has a blue-noise property,  
4 it does not follow that this property must be preserved  
5 after expansion of the superpixels selected using that ma-  
6 trix. It is the expanded superpixels that the end-user  
7 sees. This issue will be taken up shortly, and related  
8 comments appear at the end of this detailed description.  
9

10 It would be possible to provide different superpixels  
11 for each intensity level (i. e. four, if two data bits are  
12 in use), and for each random choice (again four is typi-  
13 cally enough). This implies designing  $4^3 = 64$  matrices of  
14 two-by-two elements (i. e. to double the resolution).

15 A way to simplify the problem is rotation of the  
16 roles of the planes for each random choice: this reduces  
17 by a factor of four the number of superpixels to be selec-  
18 ted. Also whenever possible it is desirable to use the  
19 stacking property that ensures monotonic behavior: a su-  
20 perpixel of a higher level includes a superpixel of lower  
21 level for the same plane and random choice.

22 Design of a compatible-superpixel set is advanta-  
23 geously guided by these goals:  
24

25 (a) Keep blue-noise quality after expansion — The  
26 matrix-based RNG described above is best used to ensure  
27 blue-noise characteristics. Using Fourier-analysis tech-  
28 niques described below, it is provided that these prop-  
29 erties are preserved in using a set of superpixels.  
30

31 (b) Reduce asymmetric artifacts — It is possible for  
32 individual superpixels to emphasize particular directions,  
33 for example the horizontal. Such tendencies individually  
34 are acceptable.

1           If, however, a common directional emphasis is present  
2 in many superpixels — for example, if all superpixels in  
3 a set emphasize the horizontal — then resulting printouts  
4 too will have excessive horizontal directionality. This  
5 problem is complicated if the system uses nonsquare super-  
6 pixels, in which simple rotations are not sufficient to  
7 eliminate directionality.

8           A consequence of all such asymmetry problems is un-  
9 wanted artifacts that defeat the randomization. Such ten-  
10 dencies can be tracked using Fourier analysis, as will be  
11 seen.

12  
13           (c) Sample the intensity levels uniformly — Most  
14 typically, printed intensity level is not linear with the  
15 number of inkdrops per superpixel producing the level.  
16 Compensation is possible through use of nonproportional  
17 numbers of drops.

18  
19           (d) Minimize conflicts across planes — Fig. 3 shows  
20 an example of superpixels 91C-94K that eliminate all drop-  
21 on-drop deposition across planes in image highlights  
22 (i. e. level 1 and less). The random number selects a  
23 column 91-94 of superpixels, for control of all the planes  
24 in a coordinated way.

25           Advantageously this technique is implemented in such  
26 a way that no two superpixels put a drop into the same im-  
27 age position. This precaution reduces graininess in the  
28 highlights.

29  
30           (e) Minimize the firing frequency of the pens — A  
31 dense horizontal line, if it must be implemented all with-  
32 in a single pass, can require a higher pen firing frequen-  
33 cy than a dense vertical or diagonal line. Therefore try-

ing to avoid dense horizontal patterns in superpixels is helpful.

## 6. FOURIER ANALYSIS OF SUPERPIXELS

Superpixel selection is advantageously based upon the goals and principles introduced above. The process of selecting superpixels, however, is not yet fully automated.

Currently as a starting point the technique uses a lower-rank superpixel that performs reasonably well, and adds extra drops one by one in each random set. For each one added, a Fourier analysis is performed to ensure that the design goals are reasonably met.

If not, then another candidate is chosen — based somewhat on intuition — and the analysis rerun. Although the process seems labor intensive, in most cases the superpixels are not bigger than four-by-four (i. e. mapping 12 to 24 dot/mm) and the number of possible candidates does not explode.

To perform the Fourier analysis the original random matrix is expanded into  $n$  matrices, where  $n$  is the number of intensity levels. Each one is the result of inserting the superpixels for that particular level using that random entry; this is repeated for each plane if different behavior across planes is expected.

(Expansion for each level makes practical sense as that can happen in an area fill. Such regions do occur, even though a primary objective is printing of photo-like images.)

For example, if the random matrix has 256 by 256 entries and the system is to use two-by-two binary superpixels with four input levels, then four binary matrices of

1 512 by 512 will be generated. Then a 2D-FFT (magnitude)  
2 of each of these four matrices is computed.

3 As an example of this, a display of such an FFT level  
4 1 (one drop per superpixel) shows a reasonable blue-noise  
5 spectrum. It has little low-frequency content 31 (Fig. 4)  
6 and reasonable high-frequency content (the rest of the  
7 image, including some peripheral energy clusters 33).

8 A like display for level 2 (two drops per superpixel)  
9 also has limited low-frequency response 32. Also, both  
10 show reasonable symmetry — as opposed to an example that  
11 derives from use of superpixels in level 2 (two drops per  
12 superpixel) that only have vertical and diagonal entries,  
13 no horizontal ones. In the latter case the result is an  
14 extended vertical structure 34 (Fig. 6), with large lobes  
15 36 at top and bottom, linked to the central, low-frequency  
16 concentration 35.

17 A better way to see the blue-noise property, however,  
18 is by examining a modified radial spectrum (MRS) derived  
19 from the 2D-FFT previously computed. This is similar to  
20 radially averaged power spectra described in Digital Half-  
21 toning by Robert Ulichney — but instead of using the pow-  
22 er spectrum this method integrates the magnitude of the  
23 2D-FFT between concentric squares 38 (Fig.8), rather than  
24 circles.

25 This method reflects better the limitation of the  
26 human eye to see diagonal lines. Computing the MRS of the  
27 superpixels shown in Figs. 4 and 5, it appears in Fig. 7  
28 that low-frequency content 37 is small, and growth 37' is  
29 steep for higher frequencies for both levels. It has been  
30 checked empirically that superpixels with higher MRS in  
31 the low frequencies are less visually pleasing.

32 These modifications to standard halftoning algorithms  
33 permit reduction of system requirements (memory, process-  
34 ing power, and storage) without decreasing the effective



quality of printed images. This is enabled by multilevel techniques that allow rendition at lower resolution, together with randomization techniques that reduce artifacts of doing so. An area of compromise is in text and line-art input, where high spatial resolution is required.

## 7. LINEARIZATION WITH NONINTEGRAL STATES

In thermal inkjet devices the image is obtained by firing an integral number of drops into a pixel grid. Multidrop devices can fire  $N$  drops in every cell of the grid, with  $N$  an integer and  $N \geq 1$  (i. e. 1, 2, 3, . . . ). The halftoning process determines the number of dots that correspond to each cell of the grid.

Once the pen architecture is closed, the drop size of the pen is fixed — establishing a discrete relationship between the amount of ink per pixel and the number of drops. This relationship in combination with the media ink-absorption characteristic ("drop gain") determines a finite set of pairs in the  $L^*$  curve (Fig. 10) — or, more precisely, optical-density curve.

There are situations, however, in which it may be desirable to deposit an amount of ink per pixel that doesn't match well to any integral number of dots. Such a requirement may arise from considerations of ink limiting, or of gradation smoothness, or other factors.

Thus for instance it may be desired to hold the maximum amount of liquid 49 per pixel to  $2\frac{3}{4}$  dots (about 33 picoliters) rather than settling for any integral breakpoint 47, 48, . . . in the number of dots. In ink-limiting terms, the effect on cockle for a given print medium may be importantly affected, and the resultant inking may

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1 be extremely useful notwithstanding the accompanying  
2 effect on optical density.

3 A particularly useful application of this technique  
4 is to obtain intermediate values 51 (Fig. 11), 52 (Fig.  
5 12) in the linearization of output density 171, 155-158 to  
6 device states 165-168. Although the superpixeling is used  
7 primarily to print at higher resolution than the halfton-  
8 ing resolution, it can also provide intermediate values  
9 along the dot axis — i. e. on average a nonintegral num-  
10 ber of dots.

## 11 12 13 8. MECHANICAL AND PROGRAM/METHOD FEATURES

14  
15 The invention is amenable to implementation in a  
16 great variety of products. It can be embodied in a prin-  
17 ter/plotter that includes a main case 1 (Fig. 13) with a  
18 window 2, and a left-hand pod 3 which encloses one end of  
19 the chassis. Within that enclosure are carriage-support  
20 and -drive mechanics and one end of the printing-medium  
21 advance mechanism, as well as a pen-refill station with  
22 supplemental ink cartridges.

23 The printer/plotter also includes a printing-medium  
24 roll cover 4, and a receiving bin 5 for lengths or sheets  
25 of printing medium on which images have been formed, and  
26 which have been ejected from the machine. A bottom brace  
27 and storage shelf 6 spans the legs which support the two  
28 ends of the case 1.

29 Just above the print-medium cover 4 is an entry slot  
30 7 for receipt of continuous lengths of printing medium 4.  
31 Also included are a lever 8 for control of the gripping of  
32 the print medium by the machine.

33 A front-panel display 211 and controls 212 are moun-  
34 ted in the skin of the right-hand pod 213. That pod en-

1 closes the right end of the carriage mechanics and of the  
2 medium advance mechanism, and also a printhead cleaning  
3 station. Near the bottom of the right-hand pod for readi-  
4 est access is a standby switch 214.

5 Within the case 1 and pods 3, 213 a cylindrical plat-  
6 en 241 (Fig. 15) — driven by a motor 242, worm and worm  
7 gear (not shown) under control of signals from a digital  
8 electronic processor 71 — rotates to drive sheets or  
9 lengths of printing medium 4A in a medium-advance direc-  
10 tion. Print medium 4A is thereby drawn out of the print-  
11 medium roll cover 4.

12 Meanwhile a pen-holding carriage assembly 220 (Figs.  
13 14 and 15) carries several pens 223-226 (Fig. 14) back and  
14 forth across the printing medium, along a scanning track  
15 — perpendicular to the medium-advance direction — while  
16 the pens eject ink. For simplicity's sake, only four pens  
17 are illustrated; however, as is well known a printer may  
18 have six pens or more, to hold different colors — or dif-  
19 ferent dilutions of the same colors as in the more-typical  
20 four pens. The medium 4A thus receives inkdrops for for-  
21 mation of a desired image, and is ejected into the print-  
22 medium bin 5.

23  
24 A very finely graduated encoder strip 233, 236 (Fig.  
25 15) is extended taut along the scanning path of the car-  
26 riage assembly 220 and read by another, very small auto-  
27 matic optoelectronic sensor 237 to provide position and  
28 speed information 237B for the microprocessor. One advan-  
29 tageous location for the encoder strip is shown in several  
30 of the earlier cross-referenced patent documents at 236,  
31 immediately behind the pens.

32 A currently preferred position for the encoder strip  
33 33 (Fig. 14), however, is near the rear of the pen-car-  
34 riage tray — remote from the space into which a user's

hands are inserted for servicing of the pen refill cartridges. For either position, the sensor 237 is disposed with its optical beam passing through orifices or transparent portions of a scale formed in the strip.

The pen-carriage assembly 220, 220' (Fig. 15) is driven in reciprocation by a motor 231 — along dual support and guide rails 232, 234 — through the intermediary of a drive belt 235. The motor 231 is under the control of signals from digital processors 71.

Naturally the pen-carriage assembly includes a forward bay structure 222 for pens — preferably at least four pens 223-226 holding ink of four different colors respectively. Most typically the inks are yellow in the leftmost pen 223, then cyan 224, magenta 225 and black 226. As a practical matter, chromatic-color and black pens may be in a single printer, either in a common carriage or plural carriages.

Also included in the pen-carriage assembly 220, 220' is a rear tray 221 carrying various electronics. Figs. 13 and 14 most specifically represent a system such as the Hewlett Packard printer/plotter model "DesignJet 2000CP", which does not include the present invention. These drawings, however, also illustrate certain embodiments of the invention, and — with certain detailed differences mentioned below — a printer/plotter that includes preferred embodiments of the invention.

Before further discussion of details in the block diagrammatic showing of Fig. 15, a general orientation to that drawing may be helpful. This diagram particularly represents preferred embodiments of the previously discussed fourth aspect of the invention.

Conventional portions of the apparatus appear as elements 70 through 78 at the left end of Fig. 15, and also



1           New image data 70 are received 191 into an image-pro-  
2           cessing stage 73, which may conventionally include a con-  
3           trast and color adjustment or correction module 72, and an  
4           error-diffusion (ED) rendition module 76 which operates at  
5           relatively low resolution e. g. 12 dots/mm. The color  
6           module 72 provides paired pixel-position and pixel-color  
7           data points to the ED module 76.

8           In addition the pixel-position data pass to a module  
9           81 that generates or receives random numbers for the ope-  
10          ration of the present invention. Preferably the random  
11          numbers are preassembled into a matrix 84 as described  
12          earlier.

13          One of those numbers when needed is read out at 193  
14          by two pointers 82, 83, which respectively respond to the  
15          output tone value 77 found by the error-diffusion block  
16          76, and the pixel-position information 75 provided from  
17          the color module 72 — also as earlier explained. A third  
18          pointer, namely identity of a color plane being rendered,  
19          may be employed as well; however, this third pointer is  
20          not shown here, as it can be unnecessary if the system  
21          will use superpixel sets that are interplane coordinated.

22          In addition to the preassembled random-number matrix  
23          84, advantageously the apparatus has some means 85 defin-  
24          ing groups of superpixels — a separate group 91C . . .  
25          94K for each tone value 77, 192 output by the ED module  
26          76. Each superpixel has a higher resolution, e. g. 24  
27          dots/mm, than the ED resolution e. g. 12 dots/mm. Each  
28          superpixel group typically includes several choices, here  
29          four, for each colorant; thus there may be four cyan choi-  
30          ces 91C, 92C, 93C, 94C for the particular tone level 192.

31          Thus if the color 192 to be printed contains cyan,  
32          the random number 193 read out from the matrix 84 is used  
33          by a number-applying module 86 to select for printing just  
34          one superpixel choice 94C for example. At the same time

1 if the target color 192 also contains another subtractive  
2 primary, yellow for example, then a superpixel 94Y (con-  
3 tinuing the same example) for that specific colorant is  
4 automatically selected from a prearranged compatible set  
5 of superpixels 94C-94K which includes the chosen su-  
6 perpixel 94C.

7 In Fig. 15 the superpixels are shown in a rank-and-  
8 file arrangement. For the given input tone 192, the  
9 choices of a specific colorant appear as the ranks; the  
10 compatible set of which each choice is a part appear as  
11 files. In the example above, the choice 94C was in the  
12 cyan rank, and the compatible set was the file 94C-94K.

13 Similarly if operation of the random-number applying  
14 means 86 instead produces a different cyan choice 92C  
15 (from the cyan rank of course — but now implicating a  
16 different file 92C-92K), and if the target color 192 also  
17 contains black, then a superpixel 92K may be selected from  
18 the same file as the chosen cyan superpixel 92C.

19 A selected superpixel, or members of a superpixel  
20 set, are read out as data 194 representing one or more se-  
21 lected superpixels 87. This selected superpixel, or group  
22 of superpixels, has the higher resolution sought for use  
23 in printing — in response to the lower resolution em-  
24 ployed in the error diffusion 76.

25 The superpixel or group of superpixels next proceeds  
26 as information 195 from the image-processing stage 73 to  
27 enter the printmasking and final-output module 88 — for  
28 specific pass and nozzle assignments, and development of  
29 control signals 220B, 231A, 220'B, 242A to drive the  
30 printing stage 220, 220', 241, 242 seen at right.

31 Integrated circuits 71 may be distributive — being  
32 partly in the printer, partly in an associated computer,  
33 and partly in a separately packaged raster image proces-

1 sor. Alternatively the circuits may be primarily or whol-  
2 ly in just one or two of such devices.

3 These circuits also may comprise a general-purpose  
4 processor (e. g. the central processor of a general-pur-  
5 pose computer) operating software such as may be held for  
6 instance in a computer hard drive, or operating firmware  
7 (e. g. held in a ROM 70 and for distribution 66 to other  
8 components), or both; and may comprise application-spe-  
9 cific integrated circuitry. Combinations of these may be  
10 used instead.

11  
12  
13 In operation the system retrieves 301 (Fig. 16) its  
14 operating program appropriately — i. e., by reading in-  
15 structions from memory in case of a firmware or software  
16 implementation, or by simply operating dedicated hardware  
17 in case of an ASIC or like implementation. Once prepared  
18 in this way, the method proceeds to the procedure 302  
19 through 325 as illustrated.

20 Principal steps, as the drawing shows, include super-  
21 pixel definition 302, image data generation or receipt  
22 306, rendering 307-308, randomized-value generation 311,  
23 superpixel selection 323 using that randomized value, and  
24 final printout 325. Within the random-value block are two  
25 major alternatives: the matrix method 312 which has occu-  
26 pied major parts of the above disclosure, and the decorre-  
27 lated-LSB method 322 which as mentioned earlier appears  
28 workable but requires extra tests and workarounds due to  
29 absence of reliable numbers when error is zero.

30 Details of the matrix method appear clearly in Fig.  
31 16, correspondingly closely to the discussions in earlier  
32 subsections of this detailed description — and also to  
33 certain of the appended claims. One interesting and im-



portant point is that the system actually is characterized by three different spatial-frequency sets:

- the spatial frequencies inherent in any image, any picture 306 as such — the frequencies corresponding to elements of a picture, e. g. faces, railway trains, trees and so on — which ordinarily vary broadly over an extremely wide range of frequencies unless a printing device is used exclusively to print area fills;
- the spatial frequencies actually appearing in superpixels 87, 91-94 selected to present the image; and
- the frequencies that occur in randomized-number matrices or sequences 84, 193, or other mechanisms that are used to select superpixels.

The invention as introduced above and as defined in certain of the appended claims is not intended to interfere any further than necessary with the first-mentioned group; to the contrary an objective is to preserve and reproduce those frequencies within reasonable limits. Recitations, for example, may thus be found in certain claims to the effect that spatial frequencies other than information in the image appear substantially consistent in the printed image.

It has been shown that the second and third groups of frequencies are advantageously managed separately. The second, for instance, is advantageously constrained by Fourier-prescreening the superpixels themselves; and the third by precomputing a randomized matrix.

1           In view of the foregoing it is believed that a person  
2 skilled in this field will find the remaining details of  
3 Fig. 16 self explanatory.

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7           The above disclosure is intended as merely exemplary,  
8 and not to limit the scope of the invention — which is to  
9 be determined by reference to the appended claims.

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